

Energy calibration at high-energy photon colliders

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ABSTRACT: Calibration of the absolute energy scale at high-energy photon ($\gamma\gamma$, γe) colliders is discussed. The luminosity spectrum at photon colliders is broad and has a rather sharp high-energy edge, which can be used, for example, to measure the mass of the Higgs boson in the process $\gamma\gamma \rightarrow H$ or masses of charged scalars by observing the cross-section threshold. In addition to the precise knowledge of the edge energy of the luminosity spectrum, it is even more important to have a way to calibrate the absolute energy scale of the detector. At first sight, Compton scattering itself provides a unique way to determine the beam energies and produce particles of known energies that could be used for detector calibration. The energy scale is given by the electron mass m_e and laser photon energy ω_0 . However, this does not work at realistic photon colliders due to large nonlinear effects in Compton scattering at the conversion region ($\xi^2 \sim 0.3$). It is argued that the process $\gamma e \rightarrow e Z_0$ provides the best way to calibrate the energy scale of the detector, where the energy scale is given by m_Z .

KEYWORDS: Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons); Performance of High Energy Physics Detectors; Pattern recognition, cluster finding, calibration and fitting methods; Detector alignment and calibration methods (lasers, sources, particle-beams).

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1. Introduction

From e^+e^- storage-ring experiments, we know that precise knowledge of the beam energy is very useful as it enables the determination of particle masses with fantastic precision, practically independent of the detector resolution and its systematic errors. The method of resonant beam depolarization at storage rings has enabled the measurement of M_Z at LEP with a relative accuracy of $2.3 \cdot 10^{-5}$, and $M_{J/\Psi}$ [1] was measured at Budker INP with a relative precision of $4 \cdot 10^{-6}$ ($\sigma_M = 12 \text{ keV}/c^2$) [2].

At linear e^+e^- colliders, there is a desire to determine the absolute beam energy using special magnetic spectrometers upstream and downstream from the interaction point (IP) with an accuracy $\sigma_E/E \sim 10^{-3}$ and 10^{-4} , respectively [3]. The luminosity-weighted center-of-mass energy can be found using the radiative-return Z production: $e^+e^- \rightarrow Z\gamma \rightarrow \mu^+\mu^-\gamma$, where γ travels at a small angle relative to the beam direction and is not detected in most cases. Since the M_Z is well-known, the c.m.s. energy can be reconstructed by measuring only the angles of muons. This method was successfully used at LEP-2 and can be used at linear e^+e^- colliders as well. The expected relative accuracy of this method is 10^{-4} for $2E_0 = 350 \text{ GeV}$ and an integrated luminosity of 100 fb^{-1} [4]. At linear e^+e^- colliders, the beam energy spread is about 0.15%. During the beam collision, a large fraction of beam particles emit beamstrahlung and ISR photons; nevertheless, a narrow spike in the luminosity spectrum remains. It can be used in measurement of particle masses and fine structures in cross sections such as the t -quark threshold, SUSY thresholds, Z' , etc. Using energy scanning with a narrow luminosity spectrum, one can measure particle masses much better than they could be measured by the detector.

Luminosity spectra at photon colliders (PC), see Fig. 1 [5, 6], are quite broad with rather sharp edges, which can be useful for measurement of particle masses. Since photons have wide spectra and various polarizations, in general case, one has to measure 16 two-dimensional luminosity distributions $d^2L_{ij}/d\omega_1 d\omega_2$, $dL_{ij} = dL_{\gamma\gamma} \langle \xi_i \tilde{\xi}_j \rangle$, where ξ_i are the Stokes parameters of the photons and the tilde denotes the second colliding beam. Among the 16 cross sections σ_{ij} , three are the

most important: those that do not vanish after averaging over the spin states of final particles and the azimuthal angles. These luminosity spectra can be found experimentally using polarization-sensitive QED processes [9]. In order to measure the spectra with sharp edges, the tracking system must have good momentum resolution. The expected resolution of tracking systems at ILC detectors $\sigma_p/p \sim 3 \cdot 10^{-5} p [\text{GeV}/c]$ for at $p > 100 \text{ GeV}/c$ [7], which is sufficient. In principle, using energy scanning by the sharp edge of the luminosity spectra, one can measure the Higgs mass with an accuracy better than 10^{-3} [10, 11]. Also, photon colliders would have an advantage in the measurement of charged scalar masses using the energy scanning near the threshold because $\sigma(\gamma\gamma \rightarrow S^+S^-) \propto \beta$, while $\sigma(e^+e^- \rightarrow S^+S^-) \propto \beta^3$. However, in a majority of physics studies the reconstruction of events will be based on information from the detector tracking system and calorimeters, which should be properly calibrated.

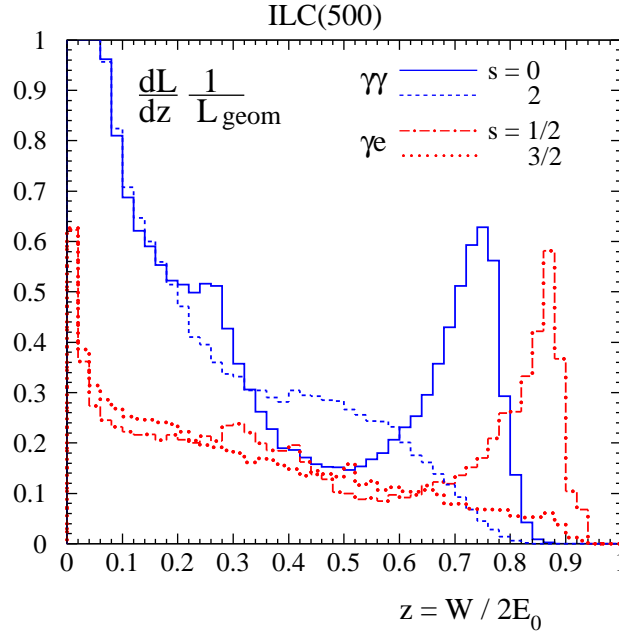


Figure 1. $\gamma\gamma$, γe luminosity spectra for ILC at $2E_0 = 500 \text{ GeV}$.

2. Nonlinear effects in Compton scattering

The maximum photon energy after Compton scattering of a laser photon with the energy ω_0 on a high-energy electron with the energy E_0 [8]

$$\omega_m = E_0 \frac{x}{x+1}, \quad \text{where} \quad x = \frac{4E_0\omega_0}{m_e^2 c^4}, \quad (2.1)$$

This expression is valid only for low laser intensities (linear Compton scattering). For $2E_0 = 500 \text{ GeV}$ and $\lambda = 1 \mu\text{m}$, the parameter $x \sim 4.5$. In order to get a conversion coefficient close to 100%, the density of laser photons should be so high that several laser photon can interact simultaneously, leading to nonlinear effects in Compton scattering[12, 5]. These effects are characterized by the

parameter $\xi^2 = e^2 \bar{B}^2 \hbar^2 / m_e^2 \omega_0^2 c^2 = 2n_\gamma r_e^2 \lambda / \alpha$, where \bar{B} is the r.m.s. strength of the electric (magnetic) field in the laser wave, n_γ is the density of laser photons. In a strong laser field, the electron acquires the effective mass $m_e^2 \rightarrow m_e^2(1 + \xi^2)$, and therefore $x \rightarrow x/(1 + \xi^2)$. This leads to the decrease of the maximum photon energy of scattered photons

$$\omega_m = E_0 \frac{x}{x+1+\xi^2}, \quad \frac{\Delta\omega_m}{\omega_m} \approx -\frac{\xi^2}{x+1} \text{ for } \xi^2 \ll x. \quad (2.2)$$

For $\xi^2 = 0.3$ and $x = 4.5$, the energy decreases by 5%. Thus, this criteria determines the acceptable ξ^2 values. Obtaining smaller ξ^2 given a fixed conversion coefficient requires a larger laser flash energy [5], which is technically problematic.

Additionally, the density of photons at the laser focus varies, which results in a spread $\sigma_{\xi^2} \sim 0.4\langle\xi^2\rangle \sim 0.28\xi^2(0)$ (obtained by simulation). If the average shift is 4%, then the additional r.m.s. energy spread is 1.5%. So, the high-energy edge of the γ spectrum is not very sharp (slope $\sim 3\text{--}4\%$), and the maximum energy is unstable due to the possible variations of the laser focus geometry (displacement, change of the spot size). The edge photon energy could be measured in γe collisions where, in the ideal case (low laser intensities), the luminosity spectrum has a very sharp edge; however, due to nonlinear effects in Compton scattering, it has a $\sim 1.5\%$ energy spread plus some additional spread due to possible variations of laser intensity at the laser focus.

We have shown that

1. At photon colliders, the main uncertainty in the energy of colliding photons is caused by the uncontrolled variation of laser intensity in the conversion region. The ratio of the maximum photon energy to the electron beam energy is not a constant due to nonlinear effects in Compton scattering; therefore, it can not be used to determine the beam energy.
2. The characteristic spread (width) of the high-energy edge of luminosity spectra is about 3–4%, which is greater than the detector resolution ($\sim 0.3\%$ at $E = 100$ GeV). The relative luminosity spectrum can be measured using QED processes ($\gamma\gamma \rightarrow l^+l^-$, $\gamma\gamma \rightarrow l^+l^-\gamma$, $\gamma e \rightarrow \gamma e$, $\gamma e \rightarrow ee^+e^-$, $\gamma e \rightarrow eZ$, etc.) [9].
3. The knowledge of the electron beam energy does not help too much; calibration of the absolute energy scale of the detector is needed.

3. Calibration of the detector

3.1 $\gamma e \rightarrow \gamma e$

In order to measure energy, one needs some value with a dimension of mass. At first sight, one can use γe collisions (the energy scale is given by the electron mass m_e). The scattering angles in collisions of electrons with energy E_0 and photons with edge energy ω_m allow one to determine $x = 4E_0\omega_0/m^2c^4$, and thus to find E_0 . For linear (low-intensity) Compton scattering, the ratio of the maximum photon energy after the $e \rightarrow \gamma$ conversion and the electron beam energy can be found by measuring the angles of scattered photon and electron (angles with respect to the initial electron direction):

$$\frac{\omega_m}{E_0} = \frac{x}{x+1} = \frac{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1 + \theta_2)}{\sin\theta_1 + \sin\theta_2 + \sin(\theta_1 + \theta_2)}. \quad (3.1)$$

By measuring the edge in distribution of this parameter, one can find the value of x , and then the beam energy. However, as we saw above, due to nonlinear effects in Compton scattering this measurement gives not x , but $x/(1 + \xi^2)$, and due to large uncertainty in ξ^2 the accuracy of the beam energy determination will be very poor:

$$\frac{\sigma_{E_0}}{E_0} \sim \frac{\sigma_{\xi^2}}{1 + \xi^2} \sim \mathcal{O}(1\%). \quad (3.2)$$

3.2 $\gamma e \rightarrow eZ$

Here, the energy scale is given by M_Z . The diagrams for this process are shown in Fig. 2. The second diagram dominates; the Z boson travels predominantly in the direction of the initial electron (the process can be viewed as $e^+e^- \rightarrow Z$ annihilation after $\gamma \rightarrow e^+e^-$ virtual decay). The dominant term in the angular distribution [13]

$$\frac{d\sigma}{d\cos\theta_Z} \propto \frac{1}{1 - \cos\theta_Z + 2m_e^2/W^2}. \quad (3.3)$$

In most cases, only Z decay products are detected (for example, $\mu^+\mu^-$), and the final-state electron escapes at a small angle. In this case, the energy of the initial electron can be express via the Z mass and the angles $\theta_{1,2}$ between the muons and direction of the initial electron:

$$E_0 \approx 0.5M_Z \sqrt{\frac{\sin\theta_1 + \sin\theta_2 + \sin(\theta_1 + \theta_2)}{\sin\theta_1 + \sin\theta_2 - \sin(\theta_1 + \theta_2)}}. \quad (3.4)$$

This expression is similar to that for the process $e^+e^- \rightarrow Z\gamma$, which is used for energy determination in e^+e^- collisions [4].

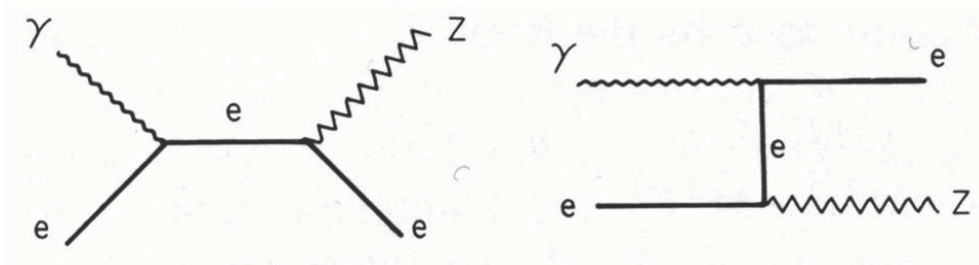


Figure 2. The process $\gamma e \rightarrow eZ$.

The cross section for unpolarized beams $\gamma e \rightarrow eZ$ is given by [13, 14]:

$$\sigma_{\gamma e \rightarrow Ze} = \frac{\tilde{\sigma}}{x} \left[\left(1 - \frac{2}{x} + \frac{2}{x^2} \right) L + \frac{1}{2} \left(1 - \frac{1}{x} \right) \left(1 + \frac{7}{x} \right) \right], \quad x = \frac{s_{\gamma e}}{M_Z^2}, \quad (3.5)$$

$$\tilde{\sigma} = \frac{\pi\alpha^2}{2M_Z^2 \sin^2 2\theta_W} [1 + (4\sin^2 \theta_W - 1)^2] = 5.9 \text{ pb}$$

$$L = \ln \frac{(s_{\gamma e} - M_Z^2)^2}{m_e^2 s_{\gamma e}} \approx 24 + \ln \frac{(x-1)^2}{x}$$

The total cross section is shown in Fig. 3.

Although this method allows the determination of the beam energy, it does not make much sense because

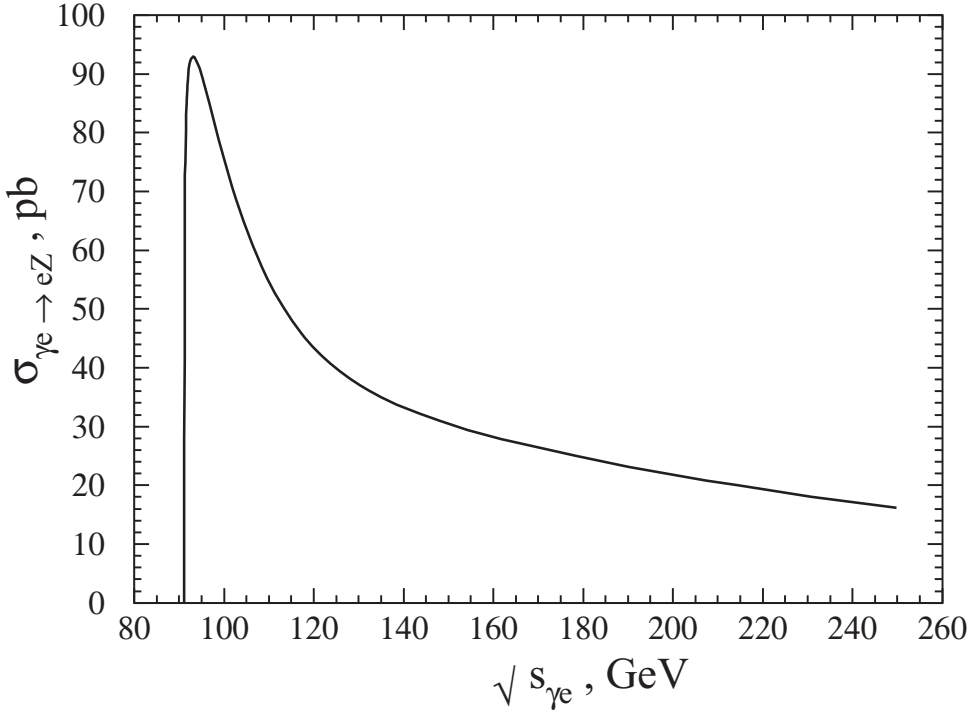


Figure 3. The cross section $\sigma_{\gamma e \rightarrow eZ}$.

- due to Compton scattering and beamstrahlung, only a rather small number of electrons have the initial beam energy E_0 ;
- the knowledge of the beam energy is not particularly useful because, due to nonlinear effects, the maximum photon energy after Compton scattering is not perfectly related to the electron energy.

What is really needed is a source of Z bosons that enables one to calibrate the detector, both the tracking system and the calorimeters. One has to introduce proper corrections in the detector response in order to reconstruct the correct Z mass. A similar strategy is used at proton (quark-gluon) colliders such as the LHC. For example, owing to Z -boson energy-scale calibration, the systematic error of $0.06 \text{ GeV}/c^2$ in the measurement of the Higgs boson mass was achieved with the ATLAS detector in the ZZ^* decay mode based on 25 pb^{-1} of integrated luminosity [15].

The cross section of the process $\gamma e \rightarrow eZ$ is rather large, only about a factor of 3 smaller than that for $\gamma e \rightarrow \gamma e$, see graphs for differential cross sections for these processes in ref. [16]. The spectrum of colliding electrons and photons at photon colliders is very broad, so many Z bosons will be produced with a low longitudinal momentum, which enables calibration of the whole detector at $P_\perp \sim 0.5 M_Z$. To ensure the linearity of detector response up to the maximum energies, one can use Z bosons emitted at large angles. The cross section for such events is smaller than the total by a factor of $\ln(E_0/m_e) \approx 10$. Decays of Z to leptons and jets allow all detector components to be calibrated.

4. Conclusion

At the photon collider, the edge energy of the photon spectrum and the electron beam energy E_0 are not exactly related due to nonlinear effects in Compton scattering. For this reason, one cannot use the process $\gamma e \rightarrow \gamma e$ to measure the beam energy and calibrate the detector. In addition, in γe collisions, electrons are non-monochromatic due to large beamstrahlung (larger than in e^+e^- due to the smaller horizontal beam size used at photon colliders). Due to these facts, precise knowledge of the initial beam is not necessary. In fact, only the absolute energy scale of the detector is needed. Such energy calibration can be done using the process $\gamma e \rightarrow eZ$, whose cross section is sufficiently large.

A beam-energy spectrometer upstream of the interaction point (foreseen for e^+e^- collisions) will be useful for fast determination of the initial beam energy, which would be particularly useful in experiments that involve beam-energy scanning. The downstream spectrometer is not possible at photon colliders due to highly disrupted beams.

Acknowledgments

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References

- [1] J. Beringer et al. (Particle Data Group), *Phys. Rev. D* **86**, 010001 (2012).
- [2] V. M. Aulchenko *et al.* [KEDR Collaboration], *New precision measurement of the J/psi and psi-prime meson masses*, *Phys. Lett. B* **573** (2003) 63.
- [3] S. Boogert, M. Hildreth, D. Kafer, J. List, K. Monig, K. C. Moffeit, G. Moortgat-Pick and S. Riemann *et al.*, *Polarimeters and Energy Spectrometers for the ILC Beam Delivery System*, *JINST* **4** (2009) P10015.
- [4] A. Hinze and K. Monig, *Measuring the beam energy with radiative return events*, eConf C **050318** (2005) 1109, [physics/0506115].
- [5] B. Badelek *et al.* *Photon collider at TESLA*, *Int. J. Mod. Phys. A*, **19** (2004) 5097, [hep-ex/0108012].
- [6] V. I. Telnov, *The Photon collider at ILC: Status, parameters and technical problems*, *Acta Phys. Polon. B* **37** (2006) 1049, [physics/0604108].
- [7] T. Behnke *et al.*, *The International Linear Collider Technical Design Report - Volume 4: Detectors*, arXiv:1306.6329.
- [8] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo and V. I. Telnov, *Colliding gamma e and gamma gamma Beams Based on the Single Pass Accelerators*, *Nucl. Instrum. Meth.* **205** (1983) 47.
- [9] A. V. Pak, D. V. Pavluchenko, S. S. Petrosyan, V. G. Serbo and V. I. Telnov, *Measurement of gamma gamma and gamma electron luminosities at photon colliders*, *Nucl. Phys. Proc. Suppl.* **126** (2004) 379, [hep-ex/0301037].
- [10] V. I. Telnov, *Physics goals and parameters of photon colliders*, *Int. J. Mod. Phys. A* **13** (1998) 2399, [hep-ex/9802003].

- [11] T. Ohgaki, *Precision mass determination of the Higgs boson at photon-photon colliders*, *Int. J. Mod. Phys. A* **15** (2000) 2605. [hep-ph/0002083].
- [12] V. B. Berestetskii, E. M. Lifshitz, and L. P. Pitaevskii, *Quantum electrodynamics*, Pergamon Press, Oxford, 1982.
- [13] F. M. Renard, *Phenomenology of Photon e^\pm Collisions*, *Z. Phys. C* **14** (1982) 209.
- [14] I. F. Ginzburg, G. L. Kotkin, S. L. Panfil and V. G. Serbo, *The W^\pm Boson Production on the Colliding e^+e^- , γe and $\gamma\gamma$ Beams*, *Nucl. Phys. B* **228** (1983) 285.
- [15] G. Aad *et al.* [ATLAS Collaboration], *Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data*, arXiv:1406.3827 [hep-ex].
- [16] A. Denner and S. Dittmaier, *Gauge boson production in electron-photon collisions*, [hep-ph/9308360].